TITLE OF THE INVENTION

POLARIZATION DIVERSITY DETECTION WITHOUT A POLARIZING BEAM SPLITTER

CLAIM OF BENEFIT OF PROVISIONAL PATENT APPLICATION

[0001]   Priority is claimed from U.S. Provisional Patent Application No. 60/394,260, filed on July 9, 2002. The contents of this provisional application are incorporated by reference.

RELATED APPLICATIONS

[0002]   This application is related to commonly-assigned PCT Application No. , , entitled "Heterodyne Optical Spectrum Analyzer," filed on July 8, 2003, and to commonly-assigned, U.S. patent application serial number 10/005,819, entitled "Apparatus and Method for the Complete Characterization of Optical Devices Including Loss, Birefringence, and Dispersion Effects," filed on December 14, 2001.

FIELD OF THE INVENTION

[0003]   The present invention relates to optical measurements, and more particularly, to a device and method for performing polarization diversity detection.

BACKGROUND AND SUMMARY OF THE INVENTION

[0004]   Mixing between a reference signal and a data signal is often necessary to extract information about an optical device. A probe signal and a reference signal originating from the same source are typically mixed, resulting in fringes that can be detected and used to asses information about the device being probed. In interferometric sensing, a reference signal is mixed with a

1

signal whose phase and/or amplitude is modified by a parameter to be measured.

[0005]   The mixing produces an interference signal, and the amplitude of the interference signal depends on how efficiently the two optical signals mix. When the two signals have the same polarization state, the mixing efficiency is 100%. When the two signals have orthogonal polarization states, no mixing occurs – 0% efficiency. Between these two limits, only the portion of the signals whose polarization states resolve onto a single polarization axis actually mix. The reduced, mixed-signal amplitude results from an unmixed component in an orthogonal polarization state. This inefficiency is usually referred to as polarization induced fringe fading.

[0006]   Polarization diversity detection overcomes polarization induced fading. One commonly known interferometric scheme that can suffer from polarization fading is Optical Frequency Domain Reflectometry (OFDR). OFDR injects a highly monochromatic beam of light into the optical system or device to be tested. The frequency of that light is varied slowly with a time-linear sweep, and the optical signal back-scattered from the optical system is detected by coherently mixing the back-scattered signal with the reference input signal. The beat frequency component of the mixed signal, (corresponding to an interference signal), is measured to determine a position of the back-scattering (reflection) point in the optical system/fiber. The interference signal amplitude also determines a back-scattering factor and an attenuation factor for the reflected light.

[0007]   U.S. patents 6,376,830 and 5,789,521 provide further details regarding OFDR measurement and are incorporated herein by reference. Reference may also be made to commonly-assigned, U.S. patent application serial number 10/005,819, entitled "Apparatus and Method for the Complete Characterization of Optical Devices Including Loss, Birefringence, and Dispersion Effects," filed on December 14, 2001.

[0008]   A single mode optical fiber supports two degenerate polarization modes. This degeneracy causes field energy to be transferred between the modes as they propagate down the fiber. This phenomenon causes the polarization fading in fiber-optic interferometers. Fig. 1 shows schematically a Mach-Zender interferometer. The arrows denote electric field (E) vector components. Polarization fading occurs whenever E_1 and E_2 are not co-linear, i.e., $\bar{E}_1 \cdot \bar{E}_2 = |\bar{E}_1||\bar{E}_2|\cos\theta$, $\theta \neq 0$. The power measured at the detector is proportional to the square of the absolute value of ($E_1 + E_2$). The interference terms of this relationship are proportional to $E_1 \cdot E_2^* + E_2 \cdot E_1^*$, where * denotes a complex conjugate. When a first coupler C1 splits the input field E_{in}, there is a chance that the split fields E_1 and E_2 in the respective interferometer arms evolve into orthogonal polarizations. As described above, in that situation, no interference fringes will be detected, and there is complete polarization fading or 0% mixing efficiency.

[0009]   A worst case scenario in which the fields interfering on the detector, E_1 and E_2, are orthogonal is shown in Figure 2. More formally, in some orthogonal basis, the fields can be written E1 = (a, 0)exp (i$\omega\tau$) and E_2 = (0, d), where τ is the propagation time difference between the two interferometer arms ($\tau = n_e L/c$, where n_e is the effective (modal) index of the fiber. The basis of a vector set includes two vectors in two dimensions or three vectors in three dimensions that are used to represent all other possible vectors. Knowing the basis of a vector set is essentially the same as knowing the coordinate system for a point in space. For example, a location may be described as being at 32 degrees North and 25 degrees West. The coordinate system is the set of latitude and longitude lines on the Earth, and the particular location is understood. The basis set is a pair of vectors, each one degree (60 nautical miles) long, with one vector pointed to the North and one vector pointed to the West.

3

[0010]   Now in the S-P basis set, shown in Figure 2 as orthogonal, the fields can be written as $E_1 = (a', b')$ exp $(i\omega\tau)$ and $E_2 = (c', d')$ so $E_1 \cdot E_2 = 0$, but $E_1 + E_2 = (a'$ exp $(i\omega\tau) + c', b'$ exp $(i\omega\tau) + d')$. Polarization diversity detection detects the s and p components (or projections onto the s and p axes) of $E_1 + E_2$ separately using two S and P detectors. The power at each detector is proportional to the modulus squared of the components of the total field:

$$P_s \propto \left| a' \exp(i\omega\tau) + c' \right|^2 \qquad\qquad (1)$$

$$P_p \propto \left| b' \exp(i\omega\tau) + d' \right|^2 \qquad\qquad (2)$$

These diversity power signals exhibit fringes even though the total field, i.e., the sum of two orthogonal fields, does not.

[0011]   Polarization diversity detection may be implemented using a polarizing beam splitter (PBS) as show in Figure 3. If the field at the PBS is E_{bs} and is given by $E_{bs} = (A, B)$ in the basis set of the polarizing beam splitter, then the measured powers at the S and P detectors are $P_s \propto |A|^2$ and $P_p \propto |B|^2$. When the PBS splits the field into different components, the crystalline structure of the PBS imposes an orthonormal basis onto which the incident field is projected. That orthonormal basis is needed to extract information contained in the E_1 and E_2 amplitudes.

[0012]   But there are drawbacks with using polarizing beam splitters. First, they are bulky and expensive. Second, polarizing beam splitters add stray reflections to the detected signals. Third, if the polarizing beam splitter is designed to operate in a particular wavelength, e.g., 1500 nm, it cannot be easily and inexpensively altered to operate at a non-standard wavelength, such as 800 nm, at least as compared to a standard optical coupler. For these and other reasons, it is an object of the present invention to perform polarization diversity detection without a polarizing beam splitter.

[0013]   The present invention performs polarization diversity detection without using a polarizing beam splitter. Field vectors from one interferometer arm are used as the basis upon which to project a field vector from the other interferometer arm. Polarization diversity detection is performed using only standard optical couplers, e.g., 50-50 couplers. A polarization beam splitter is not needed.

[0014]   A first coupler receives a first optical signal from a device or system under test and generates first and second coupler outputs. A second coupler receives a second optical signal from a reference source and generates third and fourth coupler outputs. A first polarization controller (PC) changes the polarization state of the third coupler output and generates a PC output. A third coupler generates a first combined output from the first coupler output and the PC output. A fourth coupler generates a second combined output from the second coupler output and the fourth coupler output. A first detector detects a first power of the first combined output in a first projection plane, and a second detector detects a second power of the second combined output in a second projection plane. A processor processes interference terms in the first and second powers in the first and second projection planes to determine one or more characteristics of the first optical signal.

[0015]   A second polarization controller changes the polarization of the first optical signal before it is received in the first optical coupler. The first and second polarization controllers are adjusted to calibrate the fiber optic measurement device. Different second polarization controller settings result in multiple corresponding vector measurements at the first and second detectors. The processor calculates a vector calibration matrix using these vector measurements. The processor corrects subsequent detected vector measurements using the vector calibration matrix. The corrected vector measurements ensure that the vector representation of the first optical signal are in an ortho-normal basis set.

[0016]   The OFDR components can be constructed simply using optical fiber, and if desired, from the same type of standard low-loss fiber. Matching the type of fiber throughout the optical network results in very low losses with essentially zero scattering events in the network. As a result, the OFDR produces very clean time domain measurements (only reflection events from the device under test appear).

[0017]   Another advantage of fiber-based OFDR construction is significant cost reduction and increased reliability and flexibility. A polarization controller can be implemented simply as a single loop of fiber that is moved to achieve a certain polarization state at the output. Once the loop is positioned, it need not be moved again. Couplers are constructed by melting two optical fibers together. In order to manufacture couplers for operation at widely different wavelengths, (e.g., 615nm and 1550nm), coupler manufacturers need only purchase fiber (an inexpensive commodity) designed for that wavelength and melt two sections together using the same process for all wavelengths. No re-tooling or significant changes to the process are required. As a result, couplers are readily available at all wavelengths at a reasonable price in contrast to polarization beam splitters and other bulk-optic based optical components.

[0018]   Other features, aspects, and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrated by way of example the principles of the invention. Like reference symbols refer to like elements throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019]   FIG. 1 illustrates a Mach-Zender interferometer;

[0020]   FIG. 2 illustrates orthogonal measurement field vectors E_1 and E_2 and two basis vectors S and P;

[0021]   FIG. 3 illustrates a Mach-Zender interferometer with a polarization beam splitter;

[0022]   FIG. 4 illustrates in function block format an optical frequency domain reflectometer (OFDR) for polarization diversity detection without a polarization beam splitter;

[0023]   FIG. 5 illustrates a different configuration of the OFDR shown in Fig. 4;

[0024]   FIG. 6 illustrates in further detail the detectors shown in Figs. 4 and 5;

[0025]   FIG. 7 illustrates in further detail the data acquisition block in Figs. 4 and 5;

[0026]   FIG. 8 is a vector diagram showing the measurement field vector E_1 and reference field vector E_2 each being projected and summed on each of the basis axes S and P in accordance with projections implemented by a polarization beam splitter;

[0027]   FIG. 9 is a similar vector diagram for the all coupler OFDR implementations found in Figs. 4 and 5; and

[0028]   FIG. 10 is a vector projector diagram showing E_1 projected onto virtual reference fields E'_S and E'_P.

DETAILED DESCRIPTION OF THE INVENTION

[0029]   The following description, for purposes of explanation not limitation, sets forth specific details, such as particular components, electronic circuitry, techniques, etc. in order to provide an understanding of the present invention. But it will be apparent to one skilled in the art that the present invention may be practiced in other embodiments that depart from these specific details. In other instances, detailed descriptions of well-known methods, devices, and techniques, etc. are omitted so as not to obscure the description with unnecessary detail. Individual function blocks are shown in

the figures. Those skilled in the art will appreciate that functions may be implemented using discrete components or multi-function hardware. Processing functions may be implemented using a programmed microprocessor or general-purpose computer, using an application specific integrated circuit (ASIC), and/or using one or more digital signal processors (DSPs).

[0030]   A first, non-limiting, example OFDR embodiment that does not employ a polarizing beam splitter is described in conjunction with Figure 4. An OFDR 10 includes a tunable laser 12 for generating an electric field at a particular frequency (controlled by the frequency sweep signal from processor 32) provided to a standard optical coupler 14. Any such coupler may be employed, and one non-limiting example is Gould part number 23-40355-33-01201 manufactured by Gould Fiber Optics Division of Gould Electronics of Baltimore, Maryland. Coupler 14 splits the input field E_{IN} into two electric field signals E_1 and E_2. E_1 is provided through optical coupler 36 and connector 38 to a device or system under test (DUT) 40. A back-scattered signal E_1 to be measured as a function of its reflection point along the fiber is provided through coupler 36 to a first coupler 16.

[0031]   The reference signal E_2 is provided to a second coupler 22. A polarization state of a first output of coupler 22 is changed in polarization controller 24. The output of polarization controller 24 is the reference signal E_2 in a first reference plane denoted "S" so that this reference signal is referred to as E_S. The second output of coupler 22 corresponds to the reference signal in another reference plane labeled "P" so that this signal is denoted E_P. The first output of coupler 16 is E_X and equals $M_{13}E_1$ as described below. The second output of coupler 16 is E_Y and equals $M_{14}E_1$.

[0032]   The couplers 18 and 26 output the signals $E_X + E_S$ and $E_Y + E_P$, respectively, which are detected by respective detectors 20 and 28. The output of S-detector 20 is a power P_S, and the output of P-detector 28 is a power P_P. Both powers are provided to a data acquisition unit 30 which provides digital information to processor 32. The processor 32 processes the information and

generates the desired electric field output signal E_{OUT} which is then provided to a display 34 to display one or more parameters of E_{OUT}. Such parameters may include amplitude and phase of the scattered light and the particular location at which the reflection occurs. Processor 32 sweeps the tunable laser 12 through a particular sweep range specified by a starting wavelength and a finishing wavelength, e.g., 1540nm-1580nm.

[0033] Figure 5 illustrates another example embodiment with a slightly different configuration in which the device under test 40 is coupled directly to the output of the coupler 14. Both embodiments employ a polarization controller 42 used in calibrating the OFDR 10 as will be later described.

[0034] The detectors 20 and 28 are illustrated in further detail in Figure 6. Any suitable detector may be employed, and one non-limiting example is a ThorLabs PDA 400 optical detector manufactured by ThorLabs of Newton, New Jersey. Each detector includes a photodetector 42 and an amplifier 44 coupled to a low-pass filter 46. The data acquisition block 30 includes an analog-to-digital conversion block 48 coupled to a buffer 50. The filtered output from the detector is converted into a digital format by the digital-to-analog conversion means 48, and the digital signal is stored in the buffer 50 before being processed by the data processor 32.

[0035] The vector diagram in Figure 8 shows projected fields on the S and P power detector reference planes. The reference fields S and P are assumed orthogonal—a reasonable assumption if a PBS is used. The S component or projection of the measured field E_1 is denoted E_X on the horizontal axis, and the P component or projection of the measured field E_1 is denoted E_Y along the vertical axis. The reference field E_2 is also projected onto the S and P axes. The sum of E_X and E_S is detected on the S detector 20, and the sum of the projections E_P and E_Y is detected on the P detector 28.

[0036] But when the two fields E_1 and E_2 are detected by the coupler pair 16 and 22, the S and P axes cannot be assumed to be orthogonal or even the same length. Although the interference takes place at two separate

detectors between signals traveling significantly different paths, that interference can be represented as the projection of the original signal of interest E1 onto two non-parallel vectors. To account for the non-orthonormal basis, E_1 is altered by two transforming matrices M_{13} and M_{14} prior to being projected onto the reference fields E_S and E_P as shown in Figure 9. So long as the two transforming matrixes M_{13} and M_{14} do not vary with time, this is an acceptable transformation.

[0037]   Rather than the projection of E_1 onto the S and P axes, Figure 9 shows the projection of E_X onto E_S and the projection of E_Y onto E_P. Even though the transforming matrices M_{13} and M_{14} are unknown, the reference fields E_S and E_P may still be transformed in a precise way that allows the detected fields as projections of E_1 onto some set of vectors. This is illustrated in Figure 10 in which E_1 is projected onto two non-parallel vectors $E'_S = M^{-1}{}_{13}$ E_S and $E'_P = M^{-1}{}_{14} E_S$. As will be demonstrated below, E_1 can be recovered from these projections shown in Figure 10 using a linear mathematical transformation.

[0038]   The propagation of a field in an optical fiber from one location to another through any linear section of the system (e.g., optical fiber, optical component, etc.) can be represented by a complex 2x2 matrix. This matrix will account for all effects of the linear section including loss, polarization rotation, and polarization-dependent loss. Let the propagation from coupler i to coupler j $(i, j = 1,2,3,4)$ be represented by the matrix M_{ij}. We therefore have $\bar{E}_x = M_{13}\bar{E}_1$ and $\bar{E}_y = M_{14}\bar{E}_1$. The interference terms measured at the S- and P-detectors 20 and 28 are proportional to

$$P_s \propto \bar{E}_x \cdot \bar{s}^* + \bar{E}_x^* \cdot \bar{s} = M_{13}\bar{E}_1 \cdot \bar{s}^* + \left(M_{13}\bar{E}_1\right)^* \cdot \bar{s}, \tag{3}$$

$$P_p \propto \bar{E}_y \cdot \bar{p}^* + \bar{E}_y^* \cdot \bar{p} = M_{14}\bar{E}_1 \cdot \bar{p}^* + \left(M_{14}\bar{E}_1\right)^* \cdot \bar{p}. \tag{4}$$

[0039]   As described, without a polarizing beam splitter, the vectors S and P no longer form an orthonormal basis. But knowledge of the amplitude

and relative angle between the vectors S and P allows the reconstruction of E_1 in an orthogonal basis.

[0040]   From Eqs. (3) and (4), it is seen that the detector power measurements of P_s and P_p project the vectors $M_{13}E_1$ and $M_{14}E_1$ into the S-P basis. The fact that the basis-vectors S and P are arbitrary allows use of the identity, $\bar{x} \cdot (M\bar{y}) = \bar{y} \cdot (M'\bar{x})$, where x and y are arbitrary vectors, M is an arbitrary matrix, and M' is the transpose of matrix M, to write the following:

$$\left(M_{13}\bar{E}_1\right) \cdot \bar{s} = \bar{E}_1 \cdot \left(M_{13}'\bar{s}^*\right) = \bar{E}_1 \cdot \bar{s}' \qquad (5)$$

$$\left(M_{14}\bar{E}_1\right) \cdot \bar{p} = \bar{E}_1 \cdot \left(M_{14}'\bar{p}^*\right) = \bar{E}_1 \cdot \bar{p}' \qquad (6)$$

[0041]   The vectors $\bar{s}'$ and $\bar{p}'$ act as the basis vectors onto which E_1 is projected. Knowledge of the amplitudes of and relative angle between $\bar{s}'$ and $\bar{p}'$ allows the projection of E_1 onto an orthogonal basis set. What is required is a process by which this correcting matrix can be quickly and efficiently found to transform the measurements into an ortho-normal basis set.

[0042]   Power measurements at the S and P detectors yield information about the vector field $\bar{E} = \bar{E}_x + \bar{E}_y$ in the S-P basis set. Those measurements are of the form

$$P_s = |E_x|^2 + |s|^2 + 2E_x s \cos\phi_x \qquad (7)$$

$$P_p = |E_y|^2 + |p|^2 + 2E_y p \cos\phi_y \qquad (8)$$

[0043]   Omitting dc components, we can form the vector,

$\bar{v} = \left(2E_x s \cos\phi_x, 2E_y p \cos\phi_y\right) = (E_s, E_p)$. But again E_s and E_p are not orthogonal. To remedy this, a calibration matrix, M, is determined. When it is multiplied by v, the product gives a new vector E that represents the field E_1 in a calibrated, orthogonal basis.

[0044]   The calibration begins by adjusting the polarization controllers PC_1 and PC_2 (41 and 24). With the reference laser 12 in the continuous sweep mode, PC_1 is adjusted so that the fringes observed on the P-detector 28 are maximized. When this is accomplished, the fringes on the S-detector 20 are

minimized by adjusting PC_1. When this is accomplished, PC_1 is adjusted so the fringe levels on the S- and P-detectors are approximately equal (to within $\pm 10\%$).

[0045]   Once the polarization controllers PC_1 and PC_2 are adjusted, the OFDR can be calibrated by taking measurements of $\bar{v} = \left(2E_x s \cos\phi_x, 2E_y p \cos\phi_y\right)$ for four distinct but random settings of PC_1. The following represent these measurements:

$$\bar{v}_1 = \begin{pmatrix} E_{s1} \\ E_{p1} \end{pmatrix}, \ \bar{v}_2 = \begin{pmatrix} E_{s2} \\ E_{p2} \end{pmatrix}, \tag{9}$$
$$\bar{v}_3 = \begin{pmatrix} E_{s3} \\ E_{p3} \end{pmatrix}, \ \bar{v}_4 = \begin{pmatrix} E_{s4} \\ E_{p4} \end{pmatrix}.$$

[0046]   With the above definitions, the following matrix can be formed

$$\begin{bmatrix} p & g \\ q & h \end{bmatrix} = [\bar{v}_1 \quad \bar{v}_2]^{-1}[\bar{v}_3 \quad \bar{v}_4] \tag{10}$$

where [x y] is a matrix with columns formed by the elements of the vectors x and y. Using the following set of definitions:

$$A = 1 - |p|^2 - |q|^2$$

$$B = 1 - |g|^2 - |h|^2$$

$$C = 2\operatorname{Re}[p^* q]$$

$$D = -2\operatorname{Im}[p^* q]$$

$$E = 2\operatorname{Re}[g^* h]$$

$$F = -2\operatorname{Im}[g^* h]$$

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} C & D \\ E & F \end{pmatrix}^{-1} \begin{pmatrix} A \\ B \end{pmatrix}$$

$$\alpha = x + iy$$

$$\beta = \sqrt{1 - |\alpha|^2}$$

$$\hat{M} = \begin{pmatrix} 1 & \alpha \\ 0 & \beta \end{pmatrix} [\bar{v}_1 \quad \bar{v}_2]^{-1}$$

the vector-calibration matrix is given by

$$\hat{M} = \begin{pmatrix} 1 & \alpha \\ 0 & \beta \end{pmatrix} [\bar{v}_1 \quad \bar{v}_2]^{-1}$$

Any measurement vector $\bar{v}_m = (2E_{mx}s\cos\phi_{mx}, 2E_{my}p\cos\phi_{my})$ can be corrected by performing the following multiplication

$$\bar{E} = \hat{M}\bar{v}_m$$

where, after the above multiplication, E is guaranteed to be in some orthonormal basis.

[0047]   Although the above-description is directed to the two polarization modes of standard optical fiber, optical fiber can support a variety of different modes. To handle that mode variety, one coupler and one detector would be added for each new mode present in the fiber. "Mode Controllers" corresponding to fiber loops (like the polarization controller loops) would also be used in each reference path. Calibration would be carried out using analogous linear algebra operations. The absence of stray reflections as described above means that the invention is particularly effective at measuring the very low scatter levels that come from the non-homogeneities in the optical fiber core. Optical-fiber, scatter-level measurements can be used to measure losses within an optical network independently of the manner of connection to the network.

[0048]   While the invention has been described in connection with practical and preferred embodiments, the invention is not limited to the disclosed embodiments. On the contrary, the invention covers various

modifications and equivalent arrangements included within the scope of the appended claims.